Solid-State Body-in-White Spot Joining of Al to AHSS at Prototype Scale

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LM104

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Overview

Timeline

- Project start date: Nov. 2014
- Project end date: June 2018
- Percent complete: 70%

Barriers

- Barriers addressed

  Joining and assembly. High-volume, high-yield joining technologies for lightweight and dissimilar materials needs further improvement

Budget

- Total Project Budget: $3,187K
- Total Recipient Share: 53%
- Total Federal Share: 47%
- Total DOE Funds Spent: $1,012K

  * as of 3/31/2017

Partners

- Project participants

  Honda R&D Americas, Alcoa, Dow Chemical, L&L, Cosma Engineering, G-NAC, MegaStir Technologies
  Brigham Young University, Ohio State University

- Project lead

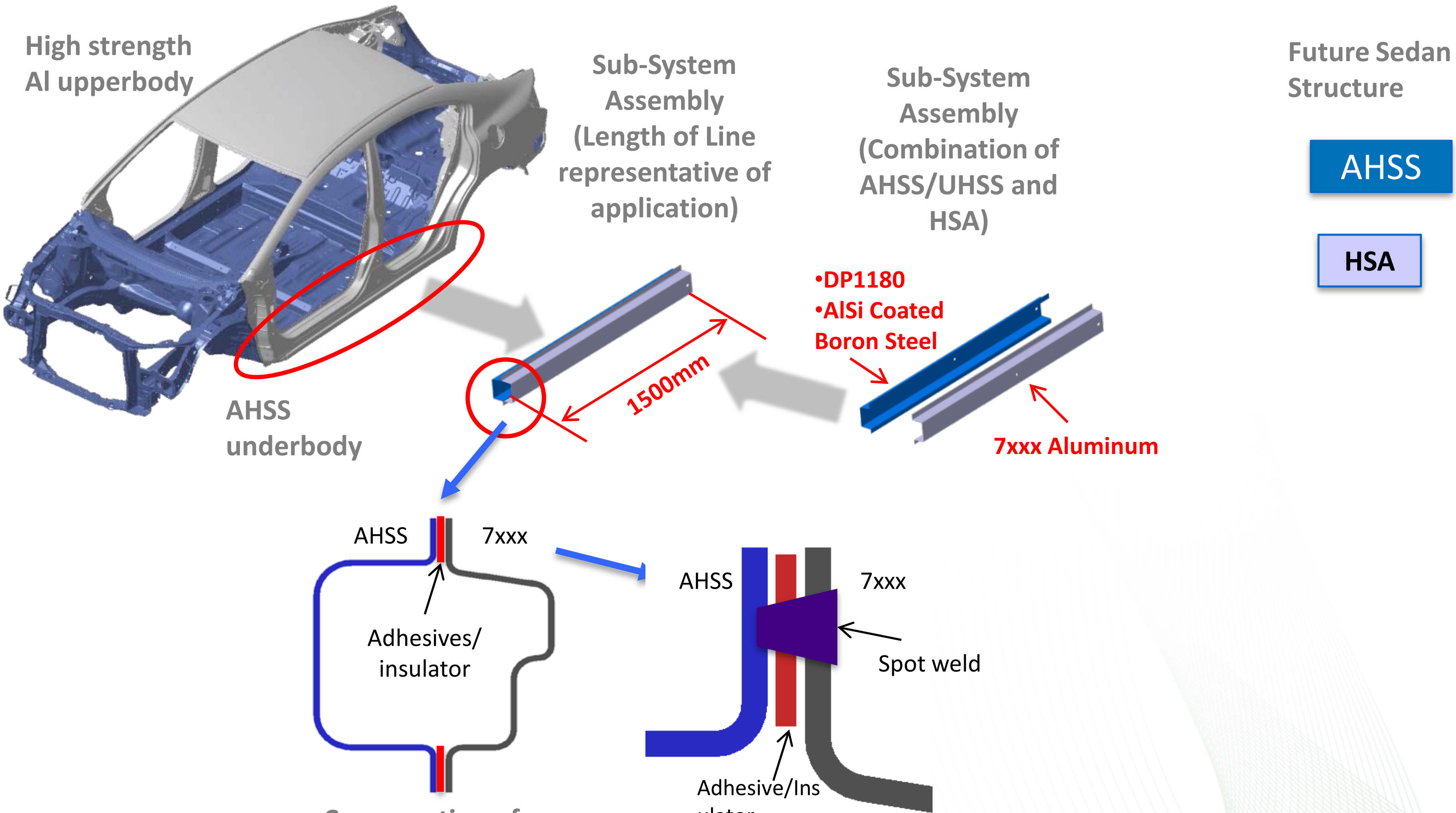
  Oak Ridge National Laboratory (ORNL)

Relevance

- **Objectives**: Develop, mature, and validate near-production readiness of a solid-state *spot joining* technology to join prototype-scale auto body-in-white (BIW) sub-systems made of advanced high-strength steel (AHSS) and 7000/6000 series high-strength aluminum alloys, to meet the dissimilar metal joining challenges in high volume mass production.

- **Impact**: The project focuses on spot joint - the most common form of joints in BIW structures of high volume production vehicles. Thus, it enables the broadest insertion of lightweight materials in BIW, and has the highest potential as a joining technology to support the reduction of petroleum consumption, environmental impacts, and economic benefits in the transportation sector. Address the goals in the DOE-VT MYPP.

Project Goal: Multi-Material Joining at Component Level



Cross-section of beam

Joint details

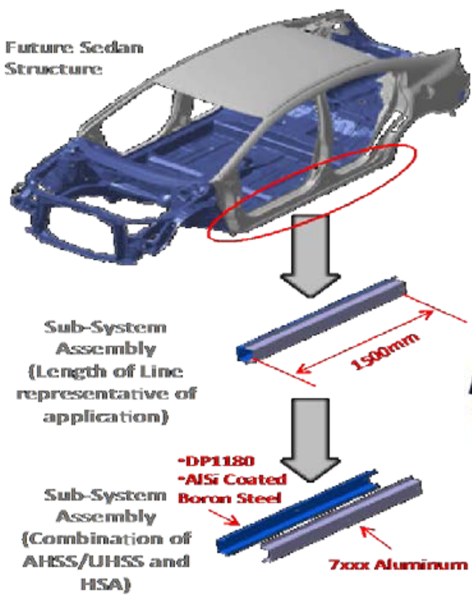
Key Milestones

Jan-15	**Define joint performance evaluation target.** Completed
Apr-15	Baseline FBJ & FSSW process development. Completed
Dec-15	Baseline process model development and validation. Completed.
Jun-16	**Pass coupon level mechanical property target matrix. Go/no-go decision Passed**
Feb-17	**Coupon level corrosion test. Delayed**
April-17	**Multi-weld development. Completed**
June-17	**Transition to Component Level Development – Down-Selection of Spot Joining Processes. Go/no-go decision**
June-17	**Distortion model due to part thermal expansion mismatch.** On-Schedule
July-17	System design for component level joining In progress
Sept-17	Weld microstructure model In progress
Dec-17	System for component joining
Mar-18	**Sub-component level joining and demonstration**
Jun-18	**Sub-component testing and reporting**

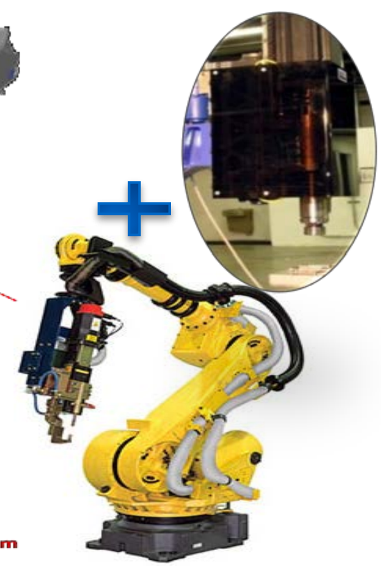
Approach/Strategy

- The proposed technology is based upon two emerging solid-state friction-heating based *spot joining* processes (FBJ and FSSW) with demonstrated success in coupon scale joining of dissimilar metals. Both processes will be refined. The winning process will be selected, further matured and integrated with an assembly-line welding robot for prototype scale BIW sub-system joining.
- An integrated weld process-structure-performance model will be employed to predict the joint performance at both coupon and sub-system levels to assist the process and sub-system design optimization.
- Prototype BIW parts will be assembled with the joining system to evaluate and validate the production readiness of the technology for BIW.

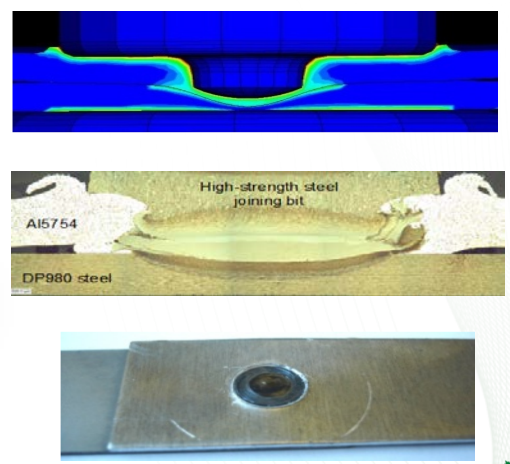
Production Relevant Prototype Scale Assembly



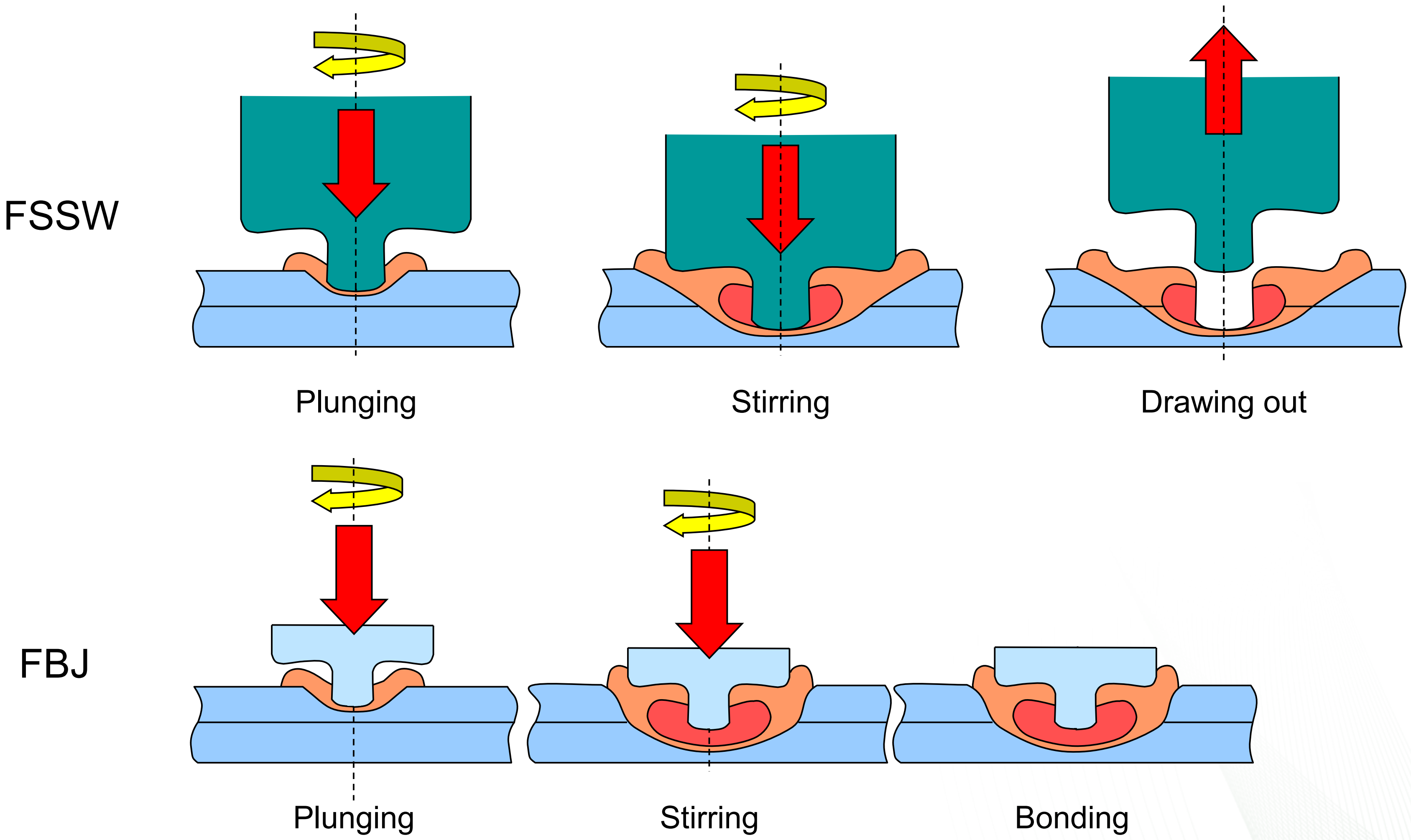
Robotic Spot Welding System



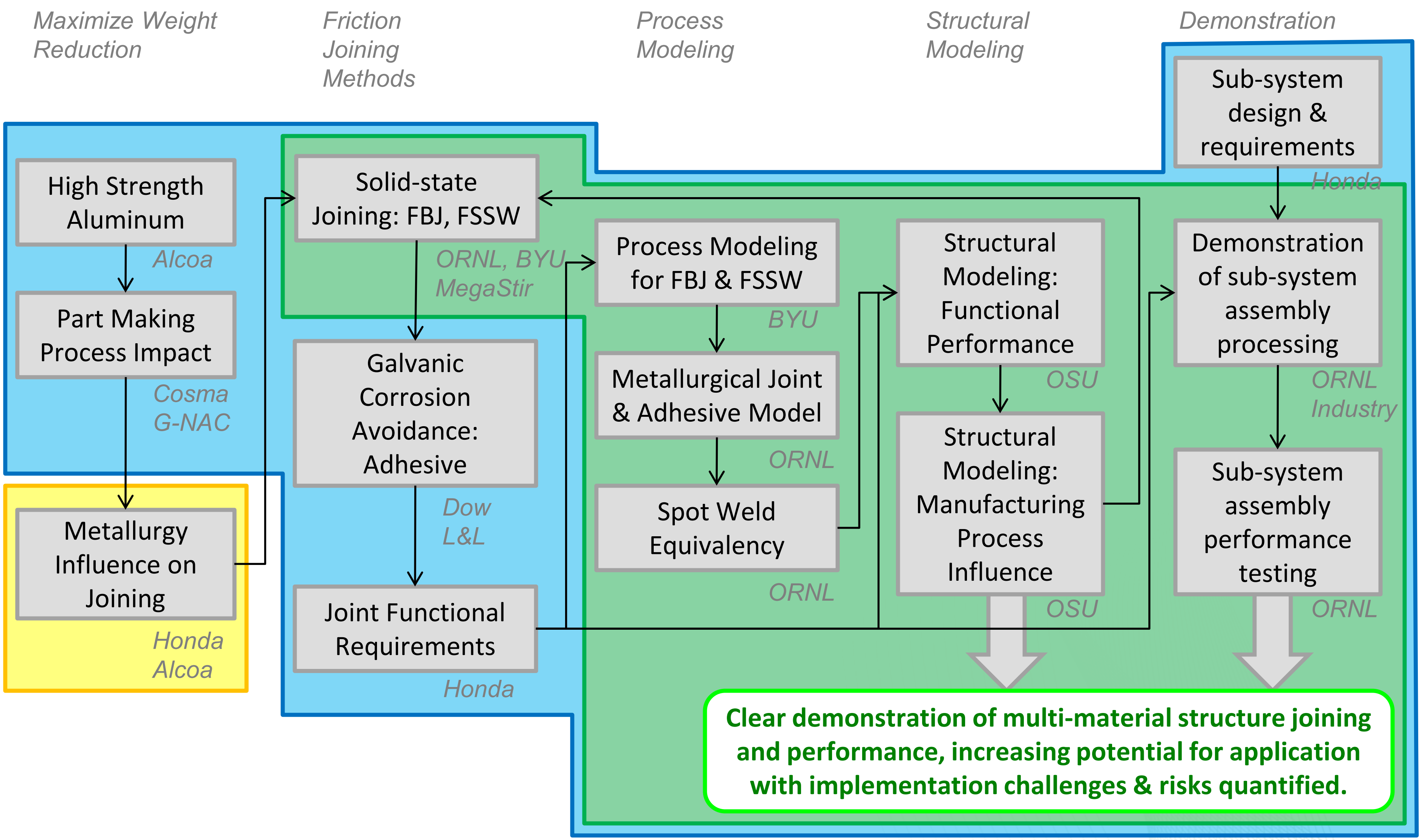
Strong Solid-State Metallurgical Bonding



Based on Two Solid-State Joining Processes: Friction Bit Joining, Friction Stir Spot Welding



R&D Plan: Roles and Responsibilities

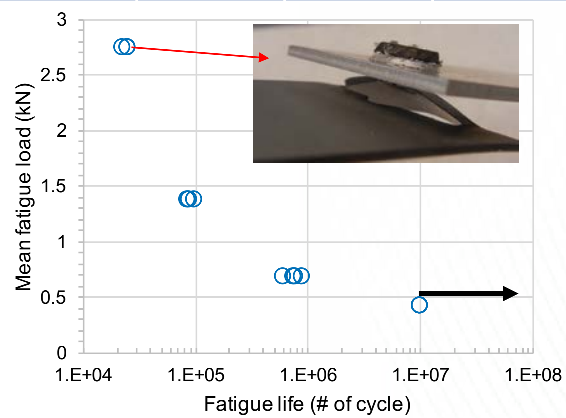


Accomplishment: Friction Bit Joining

Passed first go/no-go decision point with FBJ: meet coupon level strength targets for wide range of material combination and process conditions in FY16

Material combination		7xxx-1 /DP1180 -GA	7xxx-1 /DP1180 -GA	7xxx-2 /DP1180 -GA	7xxx-2 /DP1180 -GA	7xxx-2 /DP1180 -GA	7xxx-2 /DP1180 -GA	7xxx-1/ DP980	7xxx-1/ DP980	Strength Targets
Thickness (mm)		2.0/1.2	2.0/1.2	2.0/1.2	2.0/1.2	2.0/1.2	2.0/1.2	1.6/1.2	2.0/1.2	–
FBJ design/material		1	1	1	2	2	3	1	3	–
TSS (kN)	FBJ-A	10.0(P)	9.7(P)	8.3(P)	9.0(P)	9.9(P)	12.2/ 10.0(P)	10.3(P)	12.85(P)	>5kN
	FBJ-2	–	–	–	–	–	–	10.5(P)	12.9(P)	
CTS (kN)		1.91(P)	–	–	–	–	2.54(P)	2.77(P)	2.82(P)	>1.5kN
T-Peel (kN)		–	–	–	–	–	2.17/ 1.79(P)	–	1.63(P)	>1.5kN
TSS fatigue (10^7) @ 0.75kN 20 Hz, R=0.1		Passed	–	–	–	–		–	Passed	0.75kN

*Including FY16 results

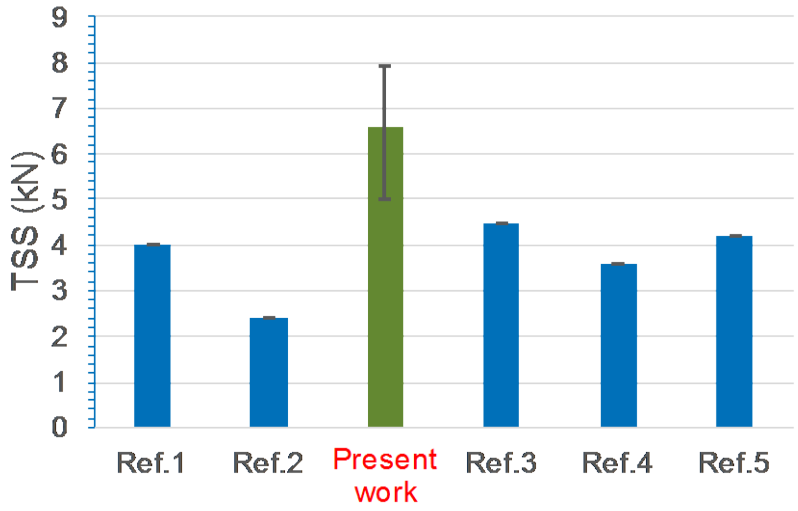


Accomplishment: Friction Stir Spot Welding

Over 50% improvement in FSSW strength through process innovations

- FSSW
  - Simplicity in equipment and operation
  - No consumables
  - Cost effective
  - Challenges: difficulties in meeting joint strength
- Process innovations to increase bonding area, control heat generation
  - Passed target TSS strength

FSSW only



FSSW only (Target: 5kN)

Sample ID	TSS(kN)
20161028#01	6.1
20161122#06	5.3
20161122#07	6.5
20161122#10	7.8
20161122#14	5.0
20161122#15	7.9
20161122#16	7.3
Aveage	6.6
STDEV	1.2

FSSW + Adhesives

Tensile shear test results			
FSSW parameters	Target value, KN	Adhesive A	Adhesive B
1	15	Didn't pass	Passed
2	15	Passed	Passed

Accomplishment: Adhesives

Adhesives offers additional strength and galvanic corrosion avoidance

- Adhesives from two team members were systematically evaluated for joint strength and potential for galvanic corrosion avoidance
- Passed strength targets for most material combinations tested in FY16
- Further considerable increase in joint strength by both adhesive team members in this year, through technology innovations.

		Target	Adhesive A			Adhesive B		
Materials			7xxx-2/ DP1180GA	7xxx-1/ DP1180	7xxx-1/ DP980GA	7xxx-2/ DP1180GA	7xxx-1/ DP1180	7xxx-1/ DP980GA
Thickness (mm)		–	2.0/1.2	2.0/1.2	2.0/1.0	2.0/1.2	2.0/1.2	2.0/1.0
TSS (kN)	Adhesive bondline thickness: A	10	P	–	P	P	–	–
	Adhesive bondline thickness: B		–	P	P	–	P	P
	Adhesive bondline thickness: C		P	P	P	P	P	P
CTS (kN)		3	P	P	F	P	P	P
Peel (kN)		Measure	Measured	–	–	Measured	–	–
TSS fatigue (10^7) 0.75 kN, 13~20 Hz, R=0.1		Measure	P	P	–	P	–	–

P: pass. F: fail

Accomplishment: Weld Bonding

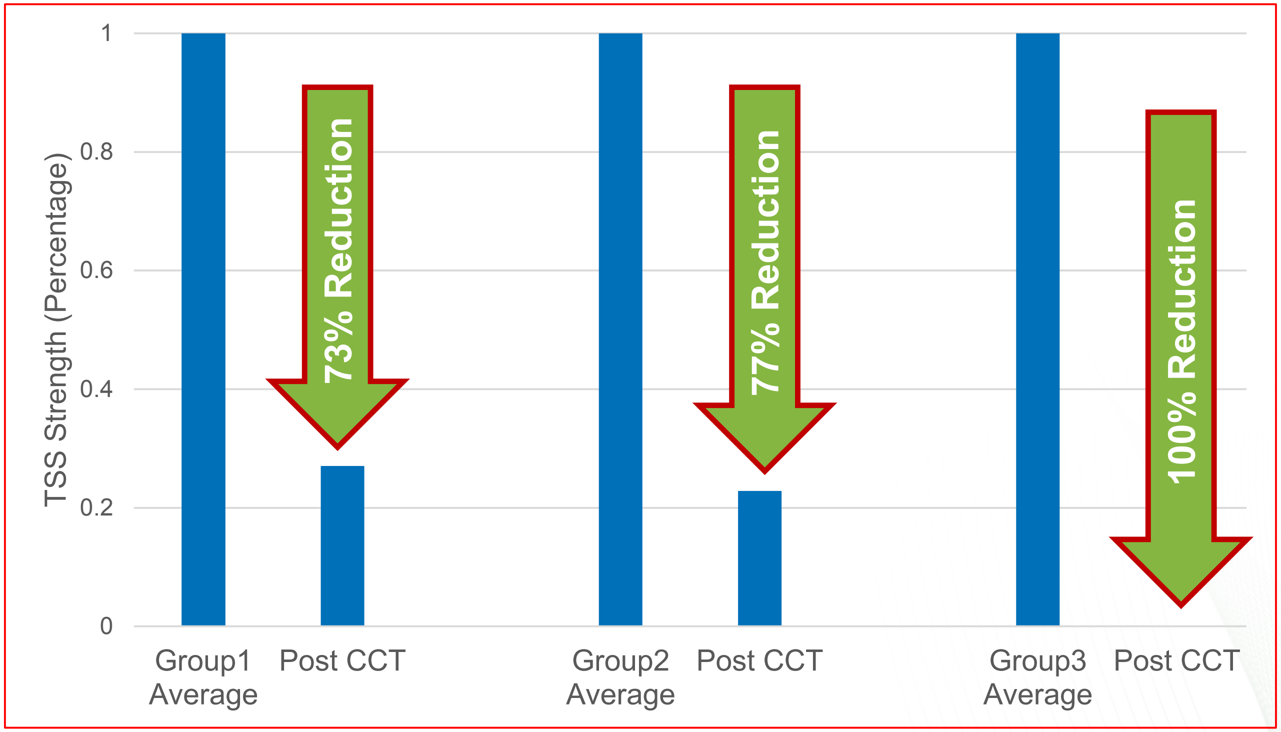
- Weld-bond, which combines spot weld and adhesives, further increases joint strength and can provides effective corrosion avoidance

	FBJ	Adhesive A	Adhesive B	Weld-bond (adhesive A)	Weld-bond (adhesive B)
Lap shear	Pass	Pass	Pass	Pass	Pass
Cross tension	Pass	Pass	Pass	Pass	Pass
T-peel	Pass	Measured	Measured	Measured	Measured
Fatigue	Pass	Pass	Pass	NA	NA

Accomplishment: Cyclic Corrosion Test

Target: Post CCT strength within 90% of original pre-CCT strength

- Significant galvanic corrosion present between substrates.
- Without adhesive, joints failed well before half way point in overall test duration.
- With adhesive, joints were compromised by corrosion initiating from trim edges.
- Possible causes identified. Additional CCT testing on-going with improved adhesive application techniques
- E-coat protection around complex FBJ geometry and aluminum substrate interaction will be studied further



Adhesive A
Adhesive B
No Adhesive

Accomplish: Multiple Welds

Investigate the process sensitivity in making multiple spot welds as an immediate step for technology scale up for the planned sub-assembly joining demonstration

- No significant process issue for multiple weld joints
- Additive joint strength of TSS for multi-welds

2 FBJ welds

Spacing (mm)	Sample ID	TSS (kN)
60	L-[redacted]10	20.8
60	L-[redacted]11	21.0
60	L-[redacted]12	21.3
60	L-[redacted]13	22.5
60	L-[redacted]14	21.5
Average		21.4
STD		0.7

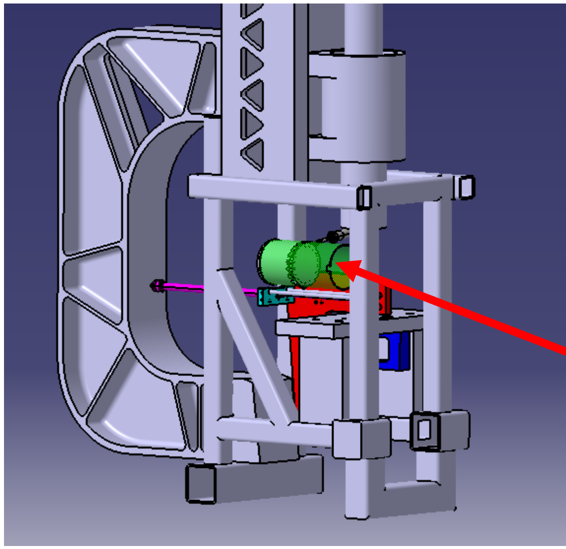
3 FBJ welds

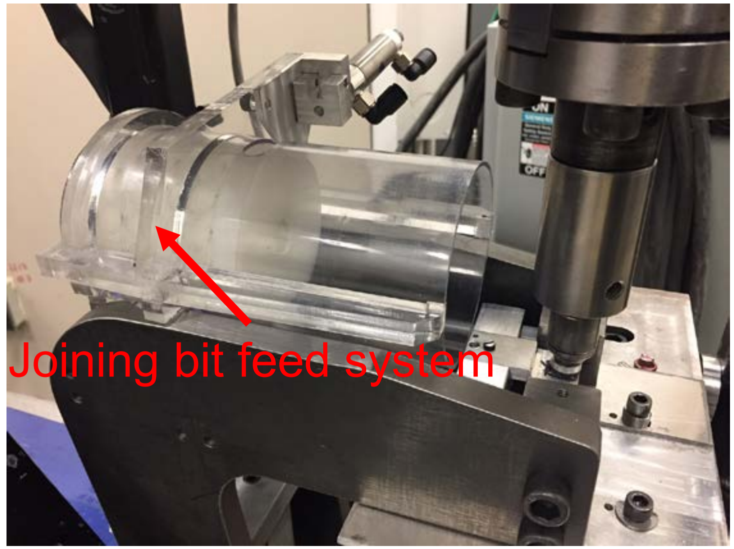
Spacing (mm)	Sample ID	TSS (kN)
40	L-[redacted]-00	30.8
40	L-[redacted]-01	32.5
40	L-[redacted]-02	30.1
40	L-[redacted]-03	24.2*
40	L-[redacted]-04	25.6*
Average		28.6
STD		3.6

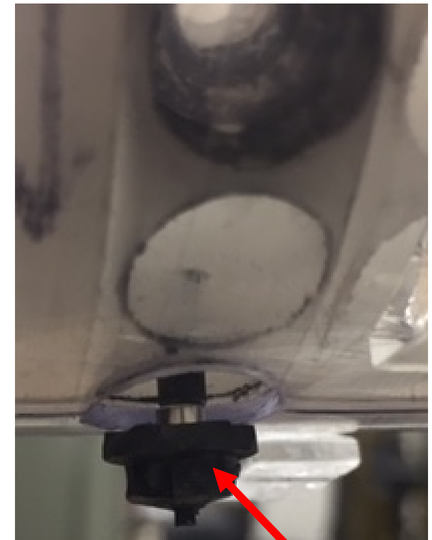
*weak weld

Accomplishment: Process Scale-up

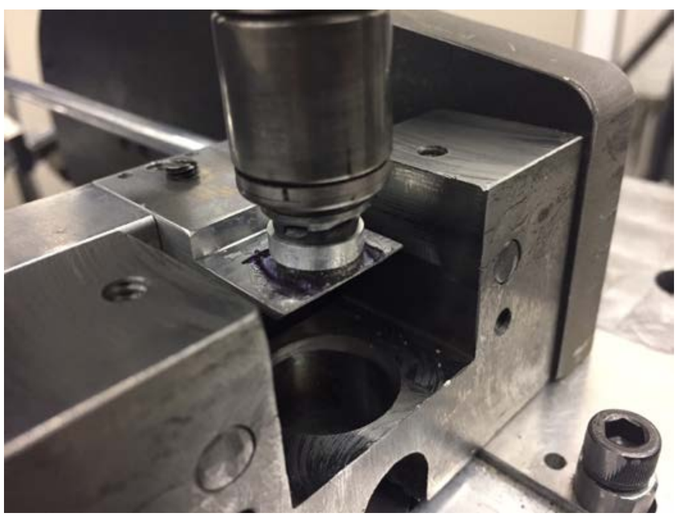
Automated joining bit feed system has been developed and integrated with FBJ system targeted for sub-assembly joining fabrication demonstration

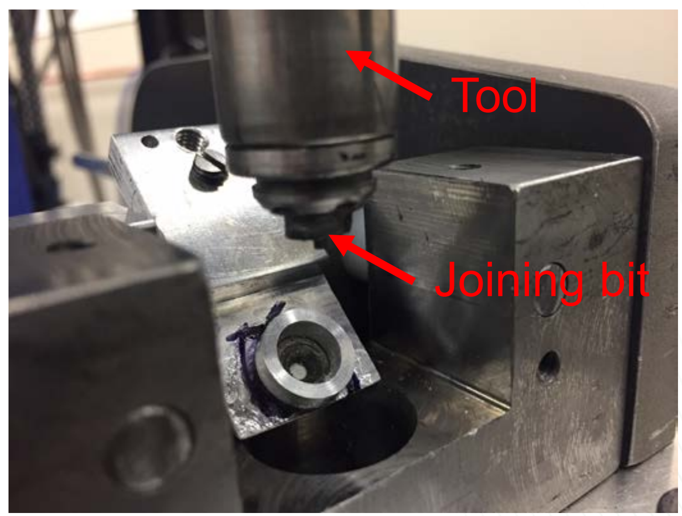






Joining bit

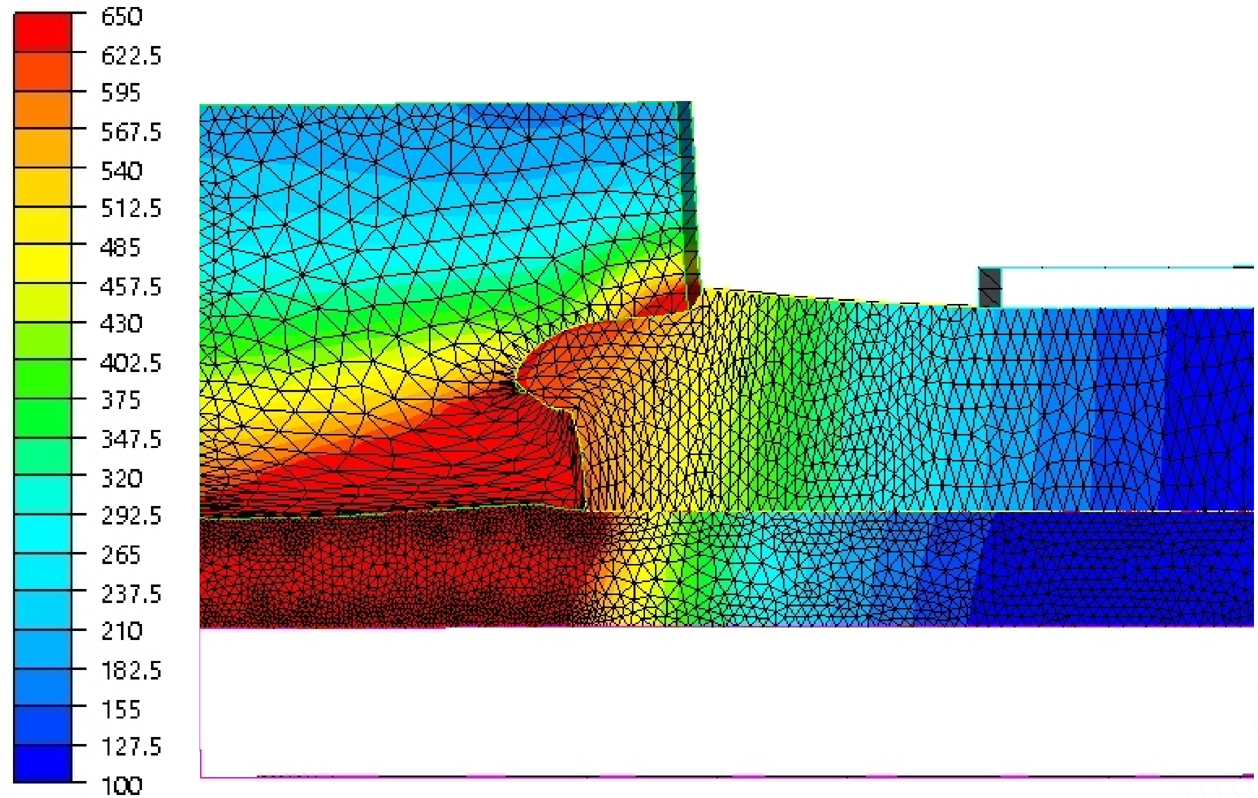


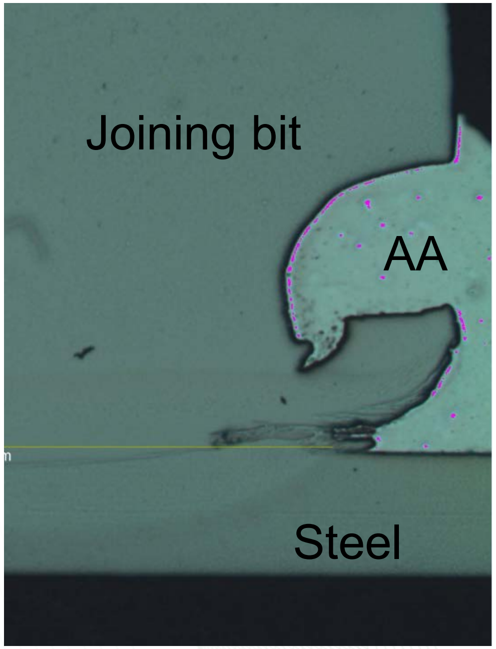


Accomplishment: Process modeling

Process model of FBJ has been developed that provides reasonable prediction of the process conditions and temperature distribution

- Output from the process model are being used to model the microstructure and properties of the joint, and thermal induced distortion during welding.



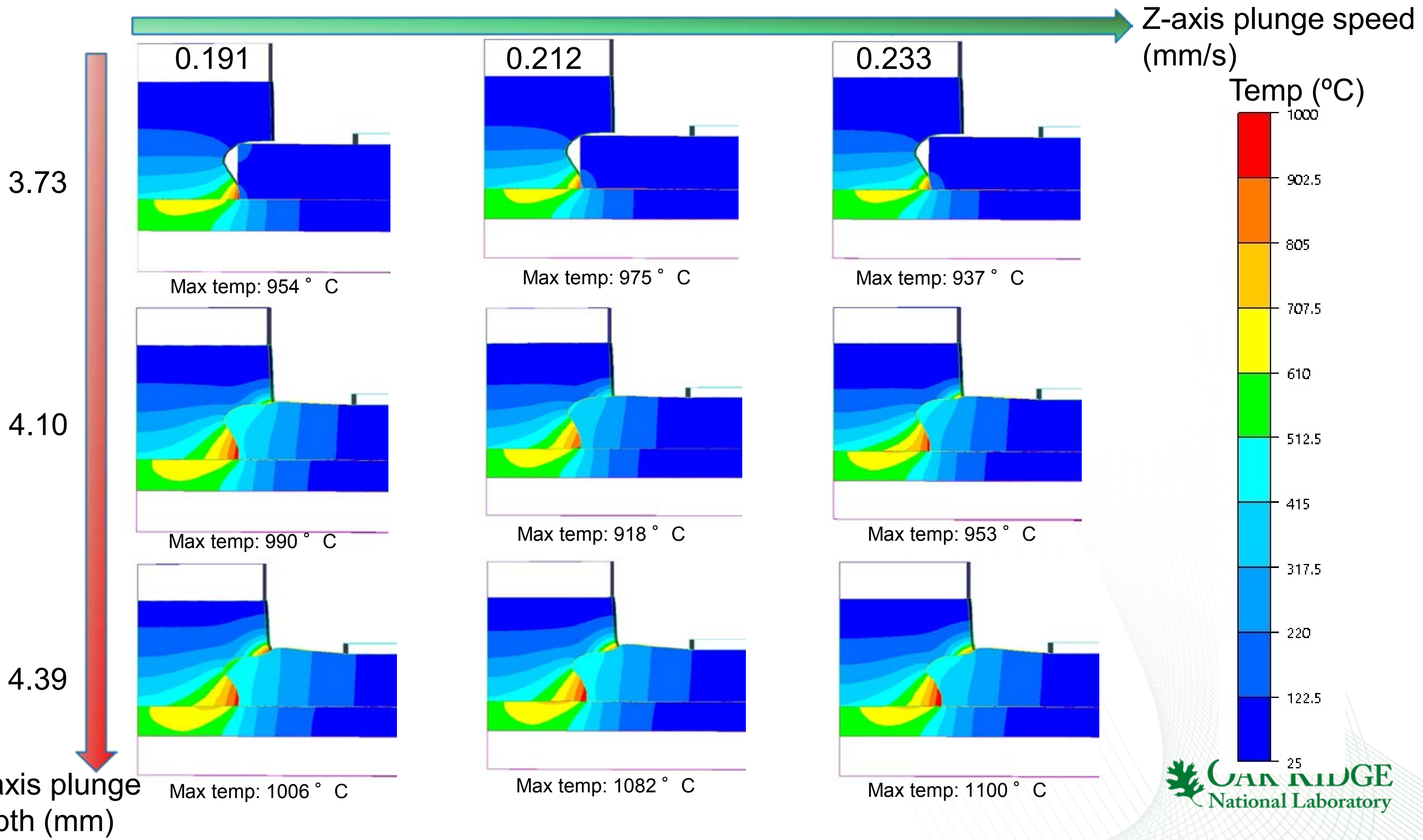


Half section of experimental joint

Accomplishment: Process Modeling

Process model has been developed for FBJ process optimization

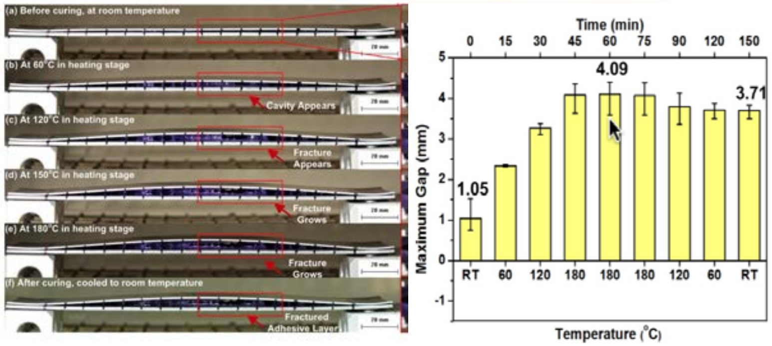
- Temperatures rise with greater plunge depth
- Material flow best approximates joint appearance for depth of 4.39mm.



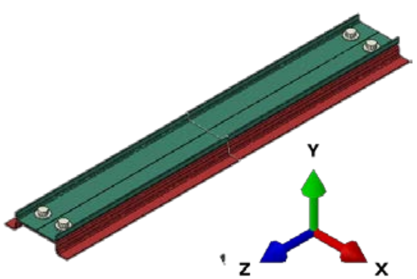
Accomplishment: Managing Thermal Expansion Mismatch Effect in Joining Dissimilar Materials

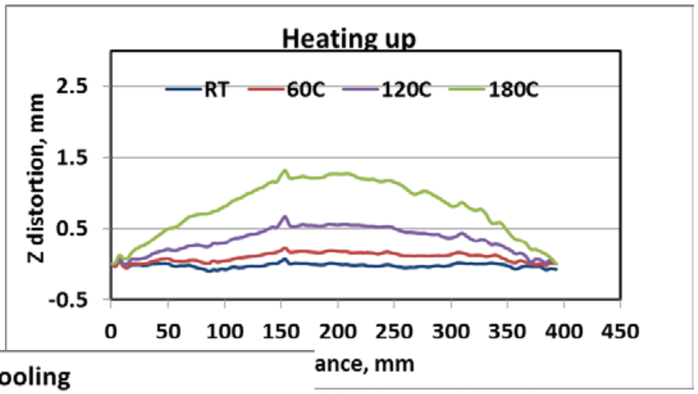
In-situ distortion measurement by Digital Image Correlation (DIC) technique

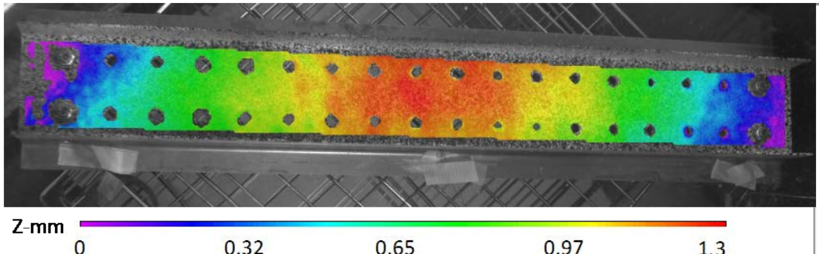
- Coefficient of thermal expansion (CTE) for aluminum alloys is almost twice that for steels; significant CTE mismatch effects are anticipated in component level body structure welding and assembly.
- In-situ DIC technique is being developed to experimentally determine the part dimensional changes during paint baking process, to support model development and validation



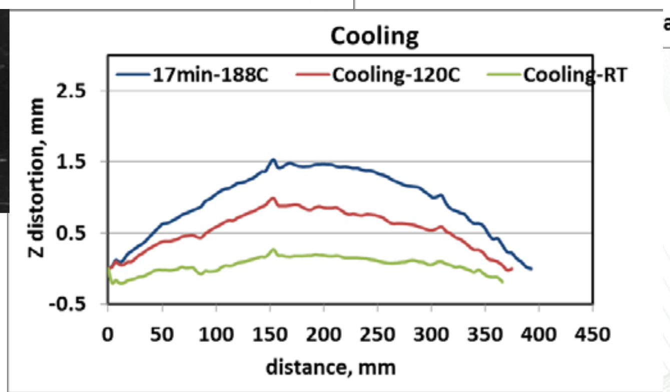
*Zhu et al. (2016) J. Manu Sci Engi, **138**(6).*







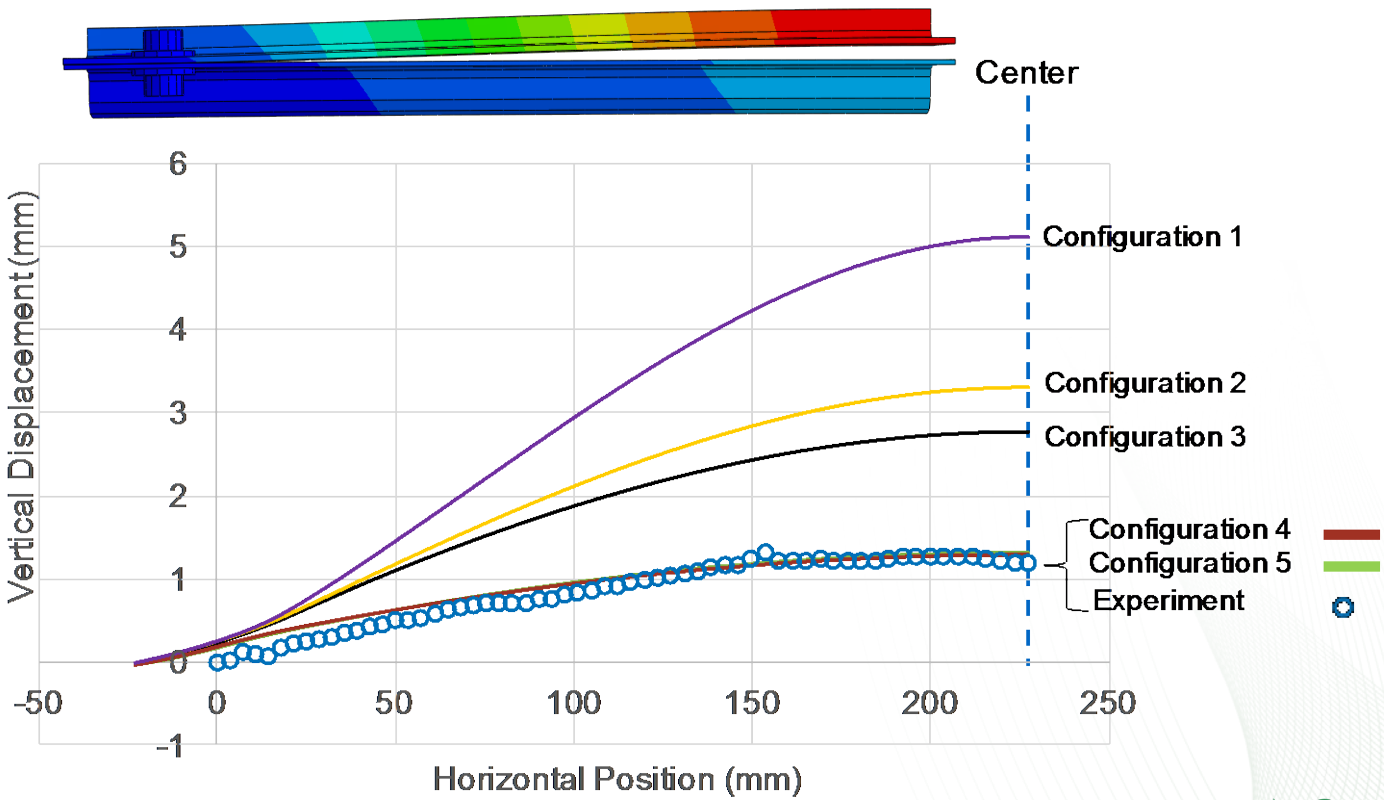
In-situ DIC results at 180C



Accomplishment: Thermal Distortion Model

Developed a FEM based model for part distortion due to thermal expansion mismatch during paint baking of adhesives

- Model is being experimentally validated
- Used to explore options to minimize thermally-induced distortion of Al-steel sub-assembly due to CTE mismatch



Effect of component geometry on thermal distortion

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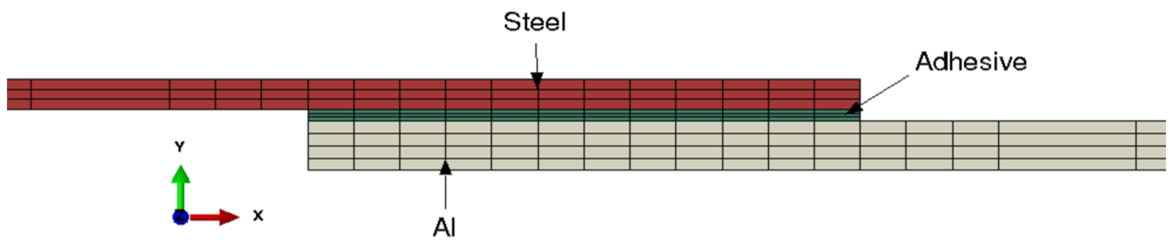
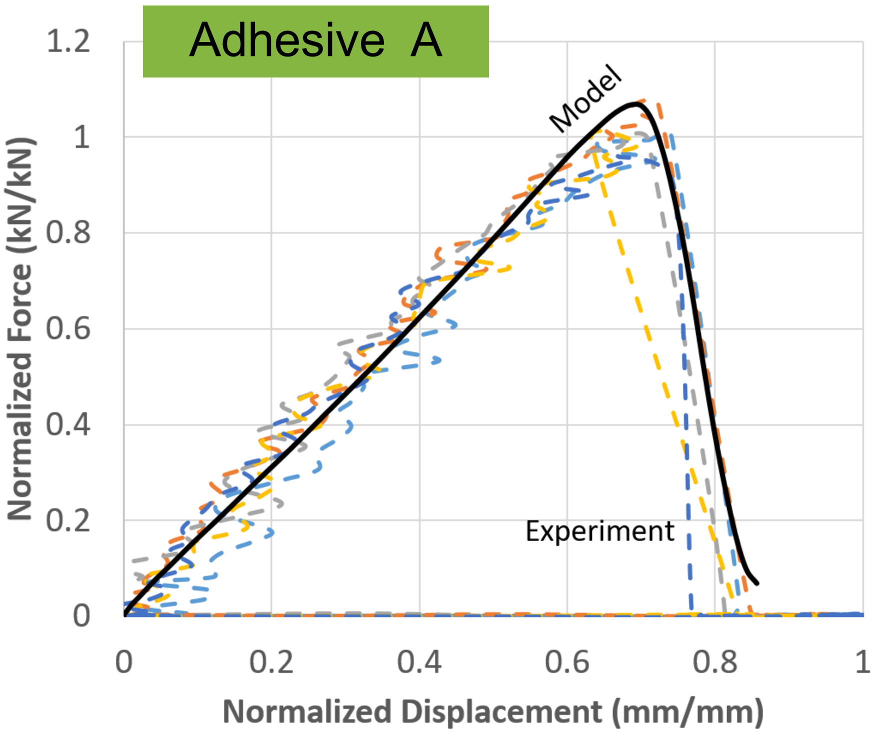
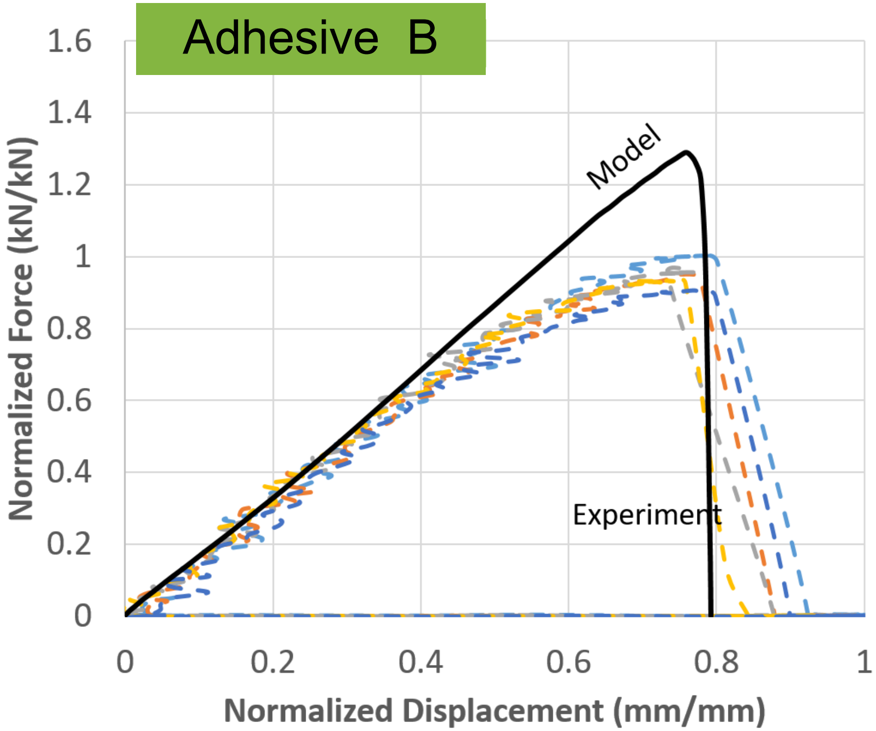
Accomplishment: Adhesive Bonding Model

Adhesive modeling with lap shear configuration has been developed to predict joint performance at coupon level to assist the joining process development and sub-system design optimization







Responses to Previous Year Reviewers' Comments

- ***The chemistry of adhesive used should be presented. An understanding of temperature at the joint interface on adhesive degradability?***

  There are two adhesive team members (Dow and L&L). Per CRADA requirement, the chemistry of adhesives are proprietary at this stage. The effects of temperature from spot joining on adhesives have been examine. They are rather localized within ~1mm from the bonded region, as revealed in FBJ process model and observation of broken samples. They have minimal effects on the joint strength and corrosion resistance from coupon level test.

- ***Predictive capability of microstructure model, and how this effort will integrate into the process***.

  The microstructure model is under development. It is based on phase transformation theories high strength steels and Al alloys, therefore applicable to the AHSS and Al alloys commonly used in auto BIW. The model is informed by experiments. The basic input of the model are chemistry, microstructure of base metal, and welding thermal cycles. The predictability of microstructure model will depend on the predictability of welding process model. In this regards, the process model, microstructure model, and performance model are integrated in this project.

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Collaborations and Industry Participations

- Roles and Responsibility of Team Members
  - ORNL (project lead) : FSSW and FBJ Process Development, Microstructure and property modeling, Adhesive Modeling
  - Honda (industry lead): Define industry need and requirement, corrosion test
  - Alcoa: Alloy Development
  - BYU: FBJ Process Development, Process Modeling
  - Cosma: Forming Analysis, Technology Validation at Component Level
  - Dow: Adhesive R&D
  - G-NAC: Forming Analysis, Technology Validation at Component Level
  - L&L: Adhesive R&D
  - Mega-Stir: FBJ system
  - OSU: Performance Modeling including adhesive bond and thermal distortion

Remaining Challenges and Barriers

- Managing part distortion due to thermal expansion mismatch of dissimilar material at the component level.
- Ensuring adequate corrosion resistance performance at the component level

Proposed Future Work

- FY17
  - Transition to Component Level Development – Down-Selection of Spot Joining Processes. Go/no-go decision. June 2017
  - Distortion model due to part thermal expansion mismatch. June 2017
  - System design for component level joining. July 2017
  - Weld microstructure model, Sept 2017

- FY18
  - System for component joining. Dec 2017
  - Sub-component level joining and demonstration. Mar 2018
  - Sub-component testing and reporting. June 2018

Any proposed future work is subject to change based on funding levels

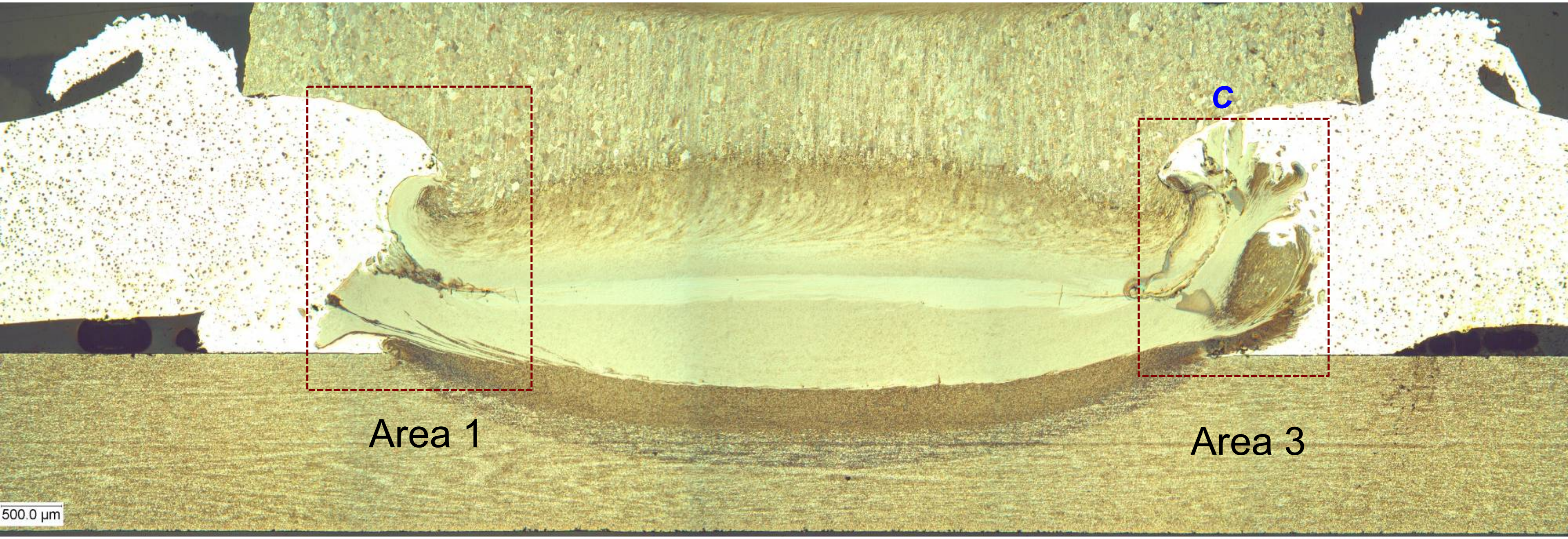
Project Summary

Relevance:	Address the critical need of dissimilar metal joining for effective use of multi-material auto-body structure for lightweighting while improving the performance and safety
Approach:	Combining solid-state spot welding and adhesive bonding to solve both joining and corrosion avoidance in use of advanced high-strength steel and 7xxx alloy for auto-body structures. Mature and validate near-production readiness of the integrated joining technology. Develop integrated weld process-property-performance model to assist the process development and multi-material structural optimization.
Technical Accomplishments	• FBJ: passed multi-weld development gate • FSSW: significant joint strength improvement achieved for FSSW • Adhesives: pass all strength requirement. • Corrosion performance of FBJ and weldbonded coupons was evaluated. Remedies to improve corrosion performance are proposed. • Integrated system scale up for component level joining: Developed automated clamping and joining bit feed systems for FBJ. • Modeling: developed FBJ process model, initial model for thermal distortion, and adhesive bond performance mode. All with coupon level experimental validations.
Collaborations:	An exceptionally strong, strategically selected and vertically-integrated project team is well suited for both technology development and future technology commercialization.
Future Plan:	Follow the SOPO R&D plan

Technical Back-up

DP980/AA5754 Weld Cross-Section

Metallurgical bonding



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Key R&D Matrixes

- Process development and demonstration
  - Development and demonstration at a coupon-scale
  - Emphasis on demonstration with prototype-scale parts
  - Performance metrics at component level
- Joint characterization
  - Microstructure, joint defect, mechanical properties
  - Corrosion performance
- Model development and validation
  - Predict the post-weld microstructure based on process parameters and input microstructure
  - Predict quasi-static failure strength
  - Predictive model to effectively control or mitigate component distortion and failure due to thermal expansion mismatch of Al and steel

Research Plan and Major Tasks

- Further develop and refine the solid-state joining process and identify process window/conditions to consistently meet the joint performance and joining cycle time requirement set forth by OEM;
- Combine adhesives with insulator properties to prevent galvanic corrosion between dissimilar metals and improve the structure performance of sub-systems;
- Design, engineer and build a near production ready solid-state spot joining system that can be integrated to an assembly-line welding robot;
- Integrate the solid-state spot joining process with an assembly-line welding robot for prototype scale BIW sub-system joining;
- Thoroughly characterize and evaluate the Al/steel joints against a set of process and performance criteria set forth by the OEM and industry team, at both coupon and sub-system scale;
- Refine and apply an integrated computational weld engineering (ICWE) modeling framework that is capable of accurately predicting the joint performance at both coupon and sub-system levels to assist the joining process development and sub-system design optimization;
- Develop an effective design and joining strategy to minimize the detrimental effects of thermal expansion mismatch between steels and aluminum alloys at sub-system component scale; and
- Demonstrate and validate the developed solid-state joining technology with prototypical BIW sub-systems.

Process selection based on FOM Analysis

	FBJ	SPR	FSSW	Ultrasonic
Material Combination				
Steel to Al	yes	yes	coated steel	coated steel
Steel to Mg	yes	difficult	TBD	coated steel
Steel Grade	All AHSS	up to DP780	All AHSS	All AHSS
Stacks	2T, 3T	2T, 3T	2T	2T
Surface Requirement	no restriction	no restriction	Zn coating	Zn coating, some cleaning
Bonding Mechanism	Metallurgical + Mechnical	Mechanical	Brazing or Metallurgical	Brazing, or metallurgical
Lap shear strength (N)				
Steel to Al	6300 - 8100	5000 - 5500	2500 - 3500	~3000
Steel to Mg	~5400	cracking	N/A	4200
Z load (N)	~ 9000	20,000 or higher	TBD	~ 2000
Process Time (sec)	1.5 - 2	< 1	<4	1.2 - 2
Weld bonding	Feasible	yes	Difficult	TBD
Consumable Bit	Yes	Yes		
Cost	Comparable to SPR	low		
Nonconsumerable Tool			Yes	Yes
Cost			High	High
Machine cost	comparable	comparable	comparable	Potentially high
Machine automation	Feasible	Yes	demonstrated	Feasible

Coupon-level performance target metrics based on input from industry team members

	Steel Baseline	Steel-Al spot weld	Steel-Al Adhesive	Steel-Al Combined
Material Top	1500P	7xxx Al	7xxx Al	7xxx Al
Material Bottom	DP1180	DP1180	DP1180	DP1180
Tensile shear strength	>18kN	>5kN	>10kN	>15kN
Cross tension strength	>5kN	>1.5kN	>3kN	>4.5kN
CTS/TSS	0.28	0.3	0.3	0.3
Peel strength	>2kN	>1.5kN	Measure	Measure
Peel/TSS	0.12	0.3	Measure	Measure
TSS Fatigue @ 10^7 cycles	0.75kN	0.75kN	measure	0.75kN

FBJ process model

Process model of FBJ has been developed that provides reasonable prediction of the process conditions and temperature distribution

- Output from the process model are being used to model the microstructure and properties of the joint, and thermal induced distortion during welding.